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WEATHERING EFFECTS ON THE GEOTECHNICAL PROPERTIES OF ARGILLACEOUS SEDIMENTS IN TROPICAL ENVIRONMENTS AND THEIR GEOMORPHOLOGICAL IMPLICATIONS

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ABSTRACT

Outcrops of young, sedimentary, argillaceous rocks with well developed fabric display rapid changes in their properties when subject to tropical weathering. The change in the materials is often accompanied by mass movement activity and the geomorphological consequence in terms of landforms is usually the development of badlands topography. Detailed field and laboratory studies have been undertaken on the Joe's River Formation, Barbados, and the Lichi Melange, Taiwan. Both are sedimentary mudrocks with well developed, scaly fabrics. Physical and geotechnical laboratory tests have been conducted on samples collected from type site locations to elucidate associations between material properties, earth surface processes and landform development. While the inherent physical properties show little or no difference in the transition from unweathered to highly weathered materials, by applying the critical state model, the mudrock geotechnical properties can be shown to change significantly. As weathering commences, material strength surprisingly increases. Only after a period of more extensive weathering do mechanical properties confirm increasingly incompetent materials. The initial strength increase appears to be due to weathering-induced modification of the fabric. The subsequent strength drop is a product of weathering-induced modification of both the fabric and the *in situ*, intact sediment. It is suggested that by applying the critical state model, a greater consideration can be gained of the geotechnical response of the sediments to weathering.

KEY WORDS weathering; critical state model; geotechnics; scaly clay; tropical environments

INTRODUCTION

Rates of landform development and the form characteristics of specific geomorphological features usually reflect factors which have direct associations with weathering rates such as climate and rock type. Research that examines weathering processes, patterns and rates in geomorphology tends to be of three types. The first type are studies which examine *in situ* rock outcrops (Caine, 1979; Motteshead, 1989), rates of particle detachment (McCarroll, 1990), surface lowering (Trudgill *et al.*, 1989) and rock mass disintegration (Tanner, 1989; Pentecost, 1991). The second type are projects which place representative stone tablets in the natural environment for specific periods of time (De Beaucourt, 1972) to establish disintegration rates. The pieces of rock are subsequently returned to the laboratory to measure parameters such as weight loss as an indicator of weathering and disintegration. The third type are laboratory simulation studies carried out under controlled conditions, such as in a climatic cabinet, to establish the effects of changes in temperature

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(Hall, 1988), moisture content (Hall, 1986) and occasionally other parameters such as salt concentrations (Smith and McGreevy, 1988; Goudie, 1993) over a specific time and set number of weathering cycles. Quantitative measures of weathering thus tend to be based on rates of rock disintegration, although recent studies have moved towards measuring other parameters in both the field (Sjöberg and Broadbent, 1991) and laboratory (Goudie *et al.*, 1992; Allison and Goudie, 1994).

Important factors during weathering are changes in the geotechnical properties of rocks and the consequence of the changes on rock mass competence and rates of disintegration (Aires-Barros and Mourza-Miranda, 1989). There are also geomorphological implications in terms of temporal rates of process operation. Nowhere are the interactions between weathering, materials, surface processes and landforms more significantly evident than in tropical environments where mudrocks are exposed. Add to this the effects of uplift in tectonically active areas and there is the potential to examine the effects of weathering on rock exposures displaying little or no signs of alteration and also on those that have become highly changed.

This paper reports the results of research undertaken to examine some of the important changes that occur in the geotechnical properties of argillaceous sediments with a well developed, pervasive fabric, under tropical weathering conditions. At some localities across the surface of the Earth, the combination of a warm, humid climate, neotectonic activity and soft, argillaceous sedimentary rocks, make it possible to study the effects of weathering over relatively short time periods. Rock outcrops displaying little or no sign of weathering may lie in close juxtaposition to others where the outcropping material has been so significantly changed that it is difficult to believe that the materials are of the same lithological unit. Such is the rate of weathering that only short durations are required for freshly exposed sediments to alter to highly weathered materials. The products of weathering, both in terms of the alteration of exposed rocks and in terms of the resulting landforms, may be distributed ubiquitously across the land surface of the Earth. For argillaceous sediment, scaly clay in this instance, weathering processes usually promote a large increase in pore volume, an appreciable change in material structure and associated changes to material mechanical properties (El-Sohby *et al.*, 1990).

In the context of this research it is important to note that mudrocks frequently have well developed microfabrics, which are seldom considered in terms of their importance in promoting weathering (Brenner *et al.*, 1981). In studies of larger, cemented rock masses, such as sandstones and limestones, it is now accepted in geomorphology that discontinuity properties such as density, orientation and continuity are important controls on material behaviour (Farmer, 1983; Selby, 1993). Smaller-scale fractures which manifest themselves as a microfabric are likely to be significant in many geomorphological contexts. The cracks will act as lines along which weathering will be preferentially active. As a consequence, those variables that are of importance with the larger rock mass discontinuities will also be significant at the smaller, macro- and microscales (Ebuck *et al.*, 1990).

With the above points in mind, the principal aims of this study are as follows:

(1) to examine the influence of microstructure on the geotechnical properties of argillaceous sediments;
(2) to elucidate changes in the mechanical properties of mudrock sediments with well developed fabric during weathering;
(3) to consider the implications of weathering-induced changes in the geotechnical properties of mudrock sediment with well developed fabrics in terms of the resulting landforms and landform development.

FIELD SITES AND SAMPLING

Of particular importance to the study are the physical characteristics of the sediment selected for examination, known as 'scaly clay'. Scaly clay is a young sedimentary mudrock, usually found in active tectonic environments. The sediment is characterized by a fine-grained, argillaceous matrix containing clasts ranging from coarse sand to pebble size, and it invariably forms the matrix component of melange deposits. Of particular importance is the pervasive fabric which is evident in freshly exposed outcrops (Figure 1). The fabric is one of curved, polished, anastomosing surfaces. A consequence of the fabric is that outcrops comprise masses of small, lenticular fragments no more than 20 to 30 mm across and occasionally much smaller

Figure 1. Outcrop of scaly clay showing fabric present within the sediment

than this. As outcrops indicate, weathering processes progressively destroy the fabric until it is all but absent in the most highly disrupted exposures. Badlands frequently develop on weathered outcrops.

One set of samples was collected on the West Indies island of Barbados (Figure 2). Barbados sits on the Lesser Antilles fore-arc ridge complex and has emerged from beneath the ocean due to collision of the Atlantic, Caribbean and South American plates (Brown and Westbrook, 1987). Subduction of the former plate is occurring at rates between 5 and 20 $mm\,a^{-1}$ (Pudsey and Reading, 1981). Uplift is active and conditions are typically tropical (Table I). Samples were collected from the Joe's River Formation. The Joe's River is an Upper Eocene scaly clay (Laure and Speed, 1984). A number of hypotheses have been presented to explain the origin of the Joe's River Formation. It is most likely that the sediments represent a mud diapir (Westbrook and Smith, 1983; Pudsey and Reading, 1981; Speed, 1983). The sediment outcrops in the Scotland District of the island (Figure 2). Landform development on the Joe's River Formation is characterized by badlands topography (Enriquez-Reyes *et al.*, 1990). Steep-sided gullies have evolved with the down-slope transfer of material being a product in part of overland flow and in part of landslide mass wasting processes (Figure 3). In its unweathered form the Joe's River Formation is highly over-consolidated and very hard, but upon exhumation the sediment weathers rapidly to form a soft, plastic material. The

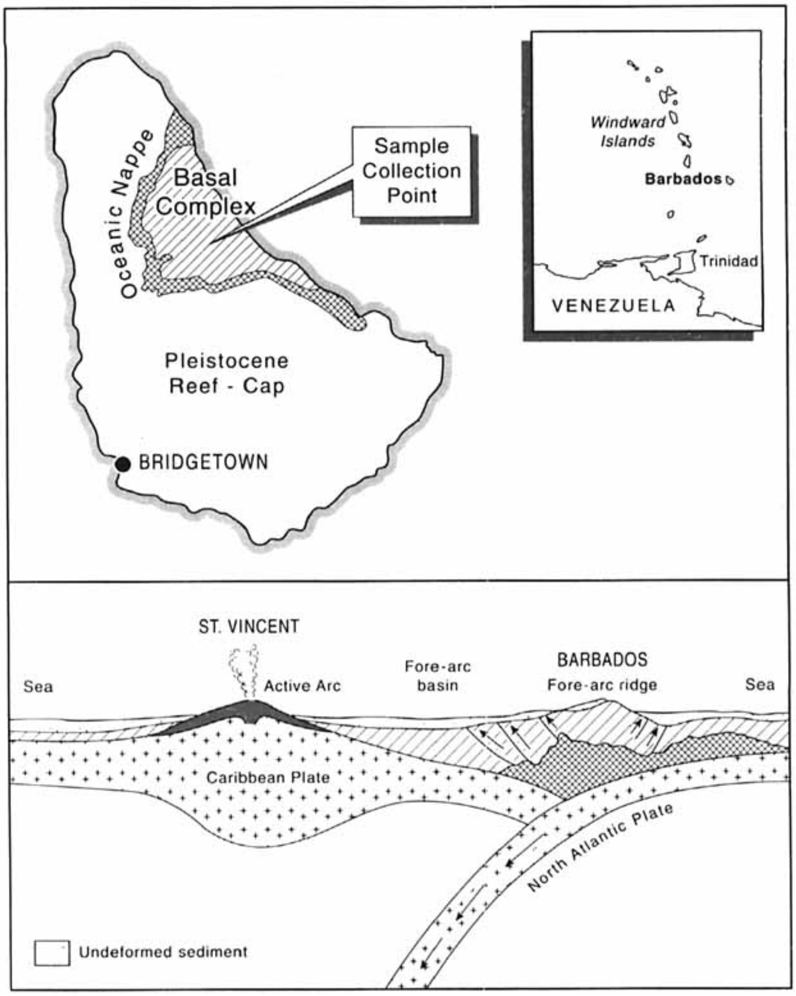

Figure 2. Location of the sample sites in Barbados

downward transition from highly weathered to unweathered material is rapid and a distinct weathering horizon can be identified over a relatively short depth of no more than 1·0 m to 1·5 m.

The second set of samples was collected from Taiwan, an island on the eastern margin of continental Asia, which sits on the boundary of the Eurasian continental plate and the Philippine oceanic plate (Figure 4). Although Taiwan is not associated with a fore-arc environment, the setting is similar to that of Barbados in that uplift rates are rapid, approaching 15 mm a^{-1} in some places (Ho, 1987). The location is one of

Table I. Mean climatic characteristics for the study sites

Country	Location	Mean annual temperature (°C) Max.	Min.	Mean annual precipitation (mm)	Scaly clay
Barbados	13°06′N 59°37′W	28	24	1525	Joe's River Formation
Taiwan	25°05′N 121°32″E	30	15	2590	Lichi Melange

Figure 3. Badlands development in the Joe's River Formation, Barbados

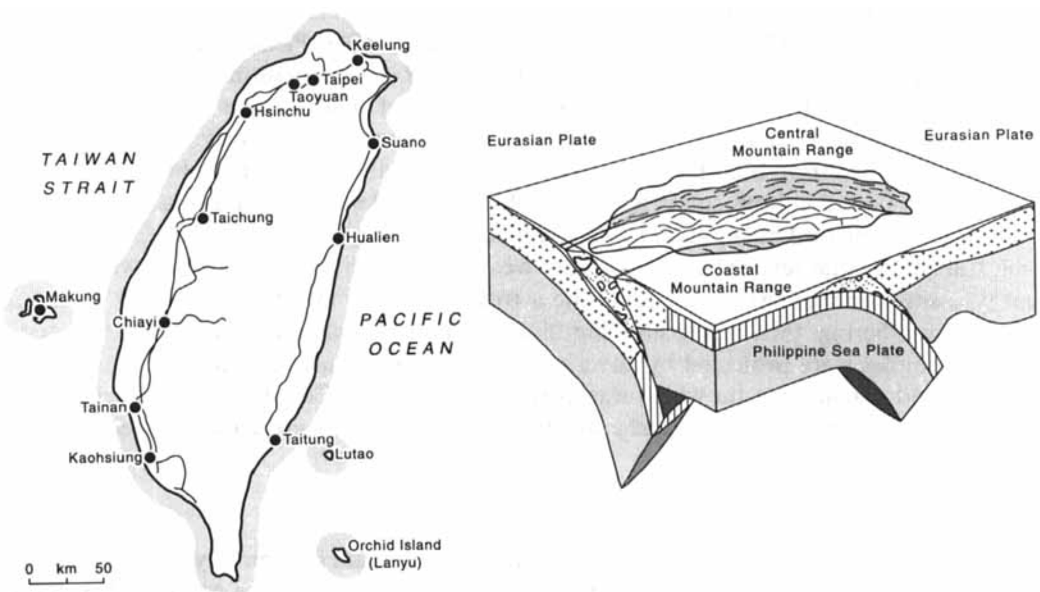

Figure 4. Location of the sample sites in Taiwan

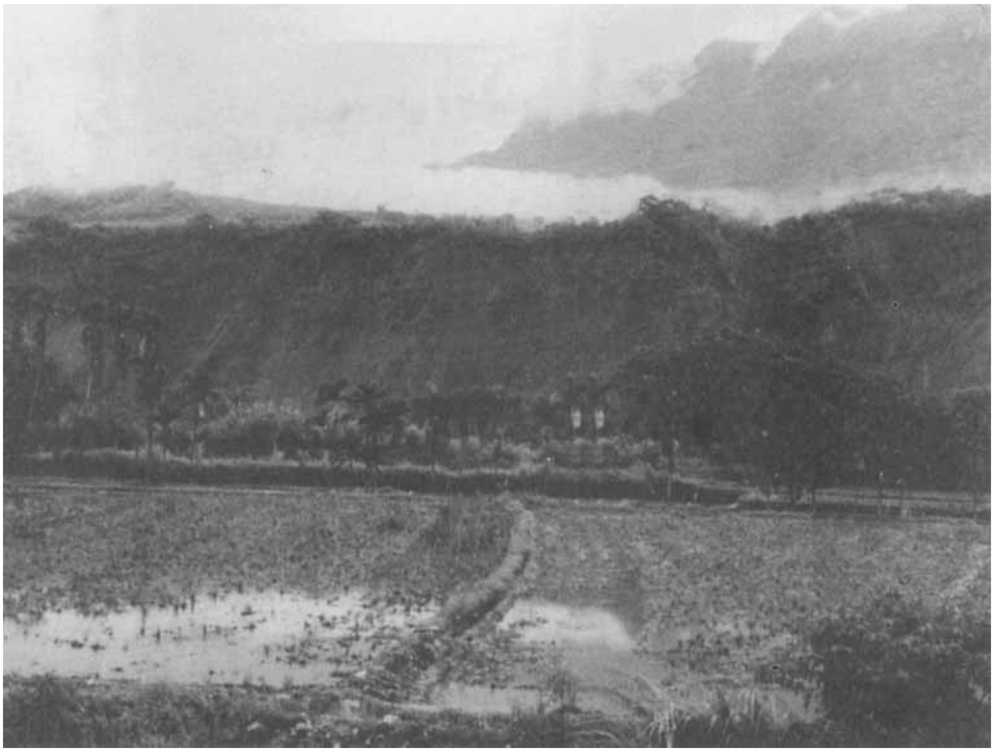

Figure 5. Badlands development in the Lichi Melange, Taiwan

arc–continent collision where the Quzon arc on the Philippine oceanic plate is over-riding the Chinese continental margin of the Eurasian plate (Biq, 1984). Climate is again tropical (Table I) with warm, humid conditions throughout the year (Lin, 1991). The scaly clay on Taiwan is found in the East Coast Mountain Range and is known as the Lichi Melange. The Lichi Melange is of Plio-Pleistocene age and displays almost identical characteristics and behaviour in outcrop as the Joe's River Formation (Figure 5). Badlands evolve as the sediment is exposed at the ground surface and rates of land surface stripping can be extreme, particularly during summer months as tropical cyclones track across the country.

Samples were collected from both Barbados and Taiwan using the same standard techniques. Three types of sediment were collected in both countries: (1) highly weathered material, immediately below the ground surface; (2) material collected at depth and displaying little or no signs of weathering; (3) sediment from the weathering transition zone referred to as partially weathered material. All materials were collected from geological type-site localities. At each sample site a trench was dug into the outcrop to expose scaly clay at all stages of weathering, then a free-standing block of material was excavated (Figure 6) and removed in pieces. The samples were protected by covering each in muslin, surrounding with plastic film, coating in paraffin wax and placing in a tin which was airtight when sealed. Consequently at each site samples of unweathered, partially weathered and highly weathered scaly clay were collected in a vertical profile.

LABORATORY METHODS

The material properties examined in the study subdivide into two main groups: physical and geotechnical. In every case, standard test techniques were adopted. The test programme was completed on unweathered (UW), partially weathered (PW) and highly weathered (HW) Joe's River Formation and Lichi Melange materials.

Figure 6. Sample collection

The inherent material physical properties tested include particle size distribution, bulk density, porosity, moisture content and index properties. Established techniques were used (British Standards Institution, 1990a,b). Individual tests were repeated three times on different specimens removed from each field sample to corroborate the accuracy of results. Particle size analysis was determined using sieve analysis and sedimentation. Apart from field moisture content, the physical properties were determined for specimens prepared for geotechnical investigation following the completion of mechanical testing. Direct associations can therefore be drawn between both parts of the laboratory schedule with a minimum of between-sample variability. Clay mineralogy was determined using X-ray diffraction.

An important part of the laboratory schedule was the determination of key mechanical properties. Geotechnical tests were undertaken using a purpose-modified triaxial cell (Figure 7). Test specimens 38 mm in diameter were prepared from field samples using a soils lathe. The preparation was particularly difficult on the unweathered samples because care had to be taken not to disrupt the scaly clay fabric. Each specimen was placed within a neoprene membrane, seated on the cell pedestal, capped at the upper end, sealed using rubber O-rings and surrounded with a perspex shield. A pressure transducer was lowered and seated on the top of the specimen. The cell was filled with a confining fluid for the application of the

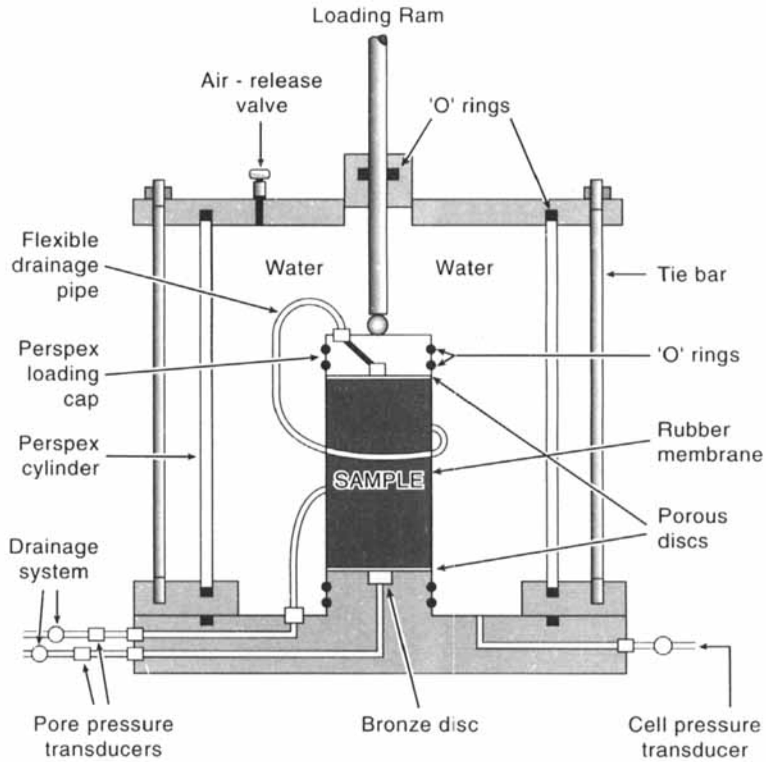

Figure 7. Triaxial cell configuration used for the geotechnical tests

minor (σ_3) stress. The principal deviatoric stress (σ_1) was applied incrementally using a motor to elevate the base of the cell while keeping the pressure transducer stationary.

Each test had two components (Table II): a consolidation phase under isotropic conditions had a defined stress regime. In some instances, such as for the unweathered samples, the time for consolidation took between six and eight weeks. Accurate data collection to equilibrium conditions for the consolidation phase of each test is more important than rapid, multiple analyses at the same confining pressure, a factor confirmed by the results examined using the critical state model. Following consolidation, each sample was sheared under undrained conditions. All data were collected using electronic pressure transducers attached to a data logger which recorded results on a two minute time-base.

SOIL MECHANICS THEORY

An important aspect of the study is the soil mechanics theory used in the analysis of the geotechnical behaviour of the scaly clay sediments. Most frequently, geomorphological studies which include some consideration of the geomechanical behaviour of earth materials examine properties such as stress, strain and shear. The variables are most frequently quantified using direct shear techniques such as the shear box, or under basic triaxial conditions. It is important to remember that there are four basic stress–strain conditions (Figure 8) and that sedimentary materials, such as those examined by this research, may be subject to a variety of different stress states between emplacement and exhumation at the ground surface (Lambe and Whitman, 1979). As a consequence it is perhaps necessary in geomorphology to move towards a more comprehensive understanding of earth material stress history in an attempt to elucidate interactions between material properties, earth surface processes and landform development.

To this end, the soil mechanics theory used here is based on the critical state model, sometimes referred to

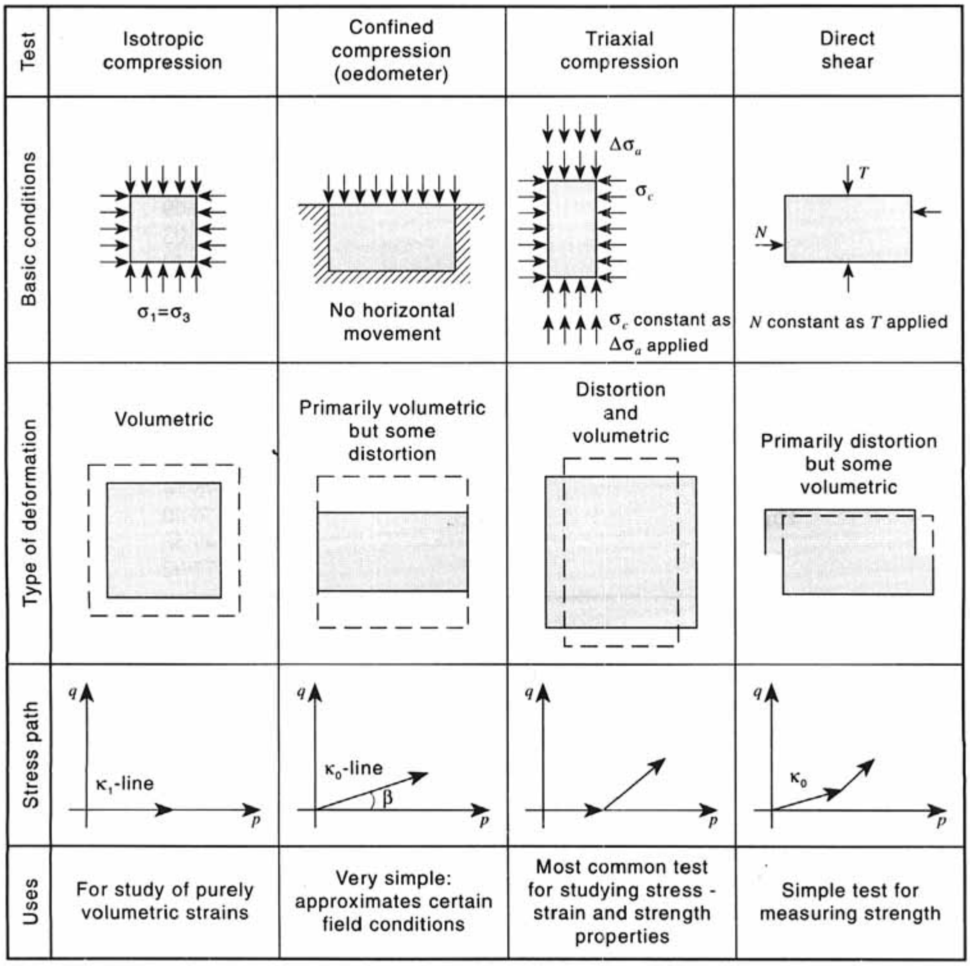

Figure 8. Basic stress–strain conditions to be considered for sedimentary materials

as the cam-clay model. The critical state model is widely employed in soil mechanics studies and there are many good reviews of the theory (e.g. Atkinson and Bransby, 1978; Wood, 1990). Cam-clay is a three-dimensional model based on key material parameters, namely the deviatoric stress (q), mean effective stress (p'), specific volume (v) and associated stress conditions. The critical state model defines important state boundaries (Figure 9). The normal consolidation line represents the stress path followed by normally consolidated soils under isotropic compression; shear behaviour is not a component of this boundary state condition. All materials prior to yield lie somewhere within the normal consolidation boundary. The critical state line is the ultimate state at which a material may exist without displaying strain or yield. If a material is subject to stress conditions which push it to the critical state line the sediment will, as the name of the boundary suggests, be at a critical point where the deformation behaviour suddenly changes and yield will accompany further strain for no further increase in applied stress. In addition, there will be no further change in material volume, whereas under isotropic conditions volume will indeed change. In other words, the critical state line identifies the location of any point representing the shear failure of a material under conditions of constant volume.

The curved surface which is bounded by the normal consolidation line and the critical state line is termed the Roscoe surface. The stress paths of normally (hydrostatic) consolidated materials which are subject to a deviatoric stress will all lie on the Roscoe surface. The precise location will depend on the specific material characteristics and the nature of the applied deviatoric stress. The stress path will gradually move across the

Table II. Geotechnical test programme

Test material	Degree of weathering	Mean effective stress (MPa)	Sample length (mm)	Porosity (%)
Joe's River	None	100	38·27	31·21
		200	38·95	32·81
		400	38·66	32·92
	Partial	100	38·31	38·04
		200	38·09	36·46
		400	37·03	37·17
	High	100	38·39	42·72
		200	38·33	41·64
		400	38·47	42·23
Lichi	None	100	74·36	20·1
		200	–	–
		400	51·96	19·3
	Partial	100	75·44	20·8
		200	77·64	19·7
		400	75·14	21·9
	High	100	76·40	25·4
		200	49·56	25·1
		400	77·92	26·3

Roscoe surface towards the critical state line as the deviatoric stress increases. The Hvorslev surface, on the other hand, marks the three-dimensional space across which the stress path of over-consolidated materials will plot under an applied deviatoric stress. Under ideal conditions, the stress path of an over-consolidated material would start at a deviatoric stress of zero ($q = 0$) and under a specific initial mean effective stress (p'), track upwards across the Hvorslev surface to the critical state line.

RESULTS

The results are best presented by first considering the physical properties of the two test materials and then by examining the mechanical characteristics.

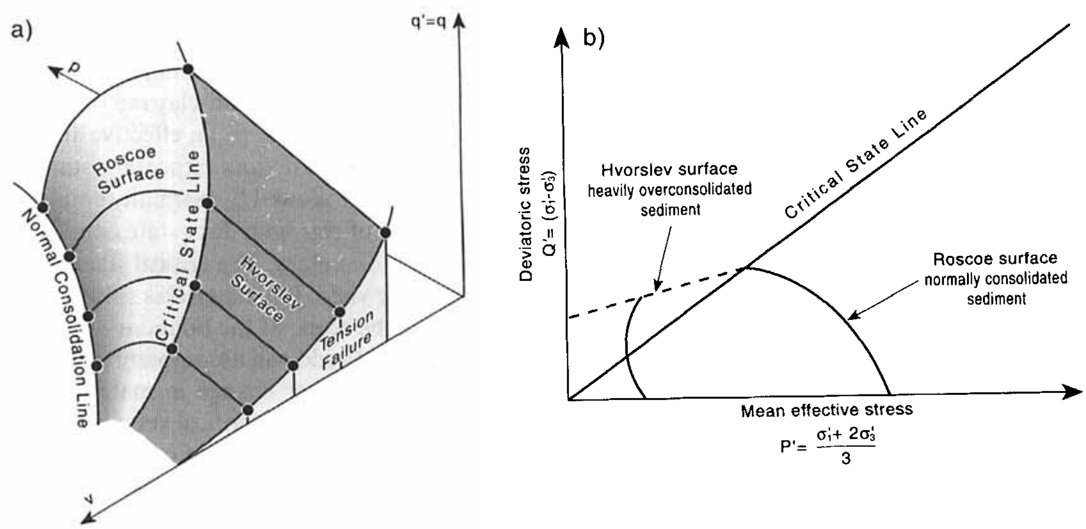

Figure 9. The critical state model: (a) in three dimensions when changes in specific volume (v) need to be considered; (b) in two dimensions when specific volume (v) is constant

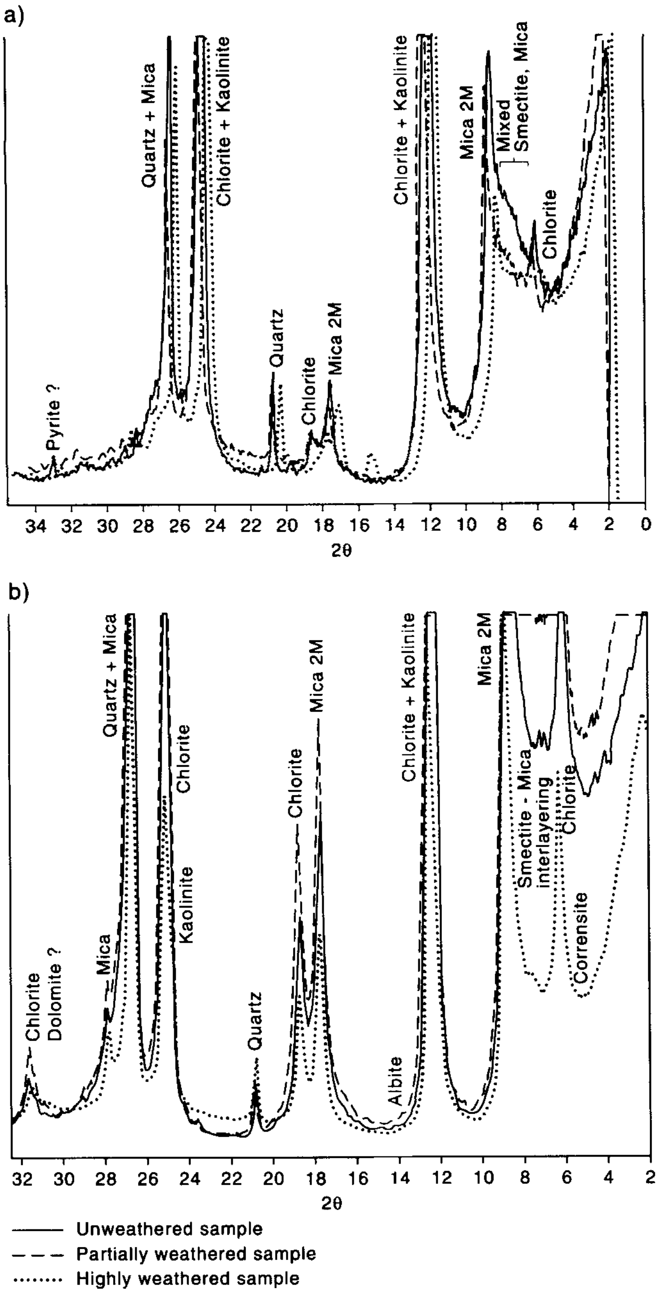

Figure 10. X-ray diffraction results: (a) Barbados; (b) Taiwan

The X-ray diffraction traces are presented in Figure 10. There are two noticeable characteristics. First, differences in clay type within a site for unweathered, partially weathered and highly weathered materials are largely insignificant. There is some variation in the Lichi Melange (Figure 10b), but the differences in the diffraction plot do not represent major variations in clay type or percentage. In other words, any variation in the geotechnical behaviour of the Joe's River Formation and the Lichi Melange sediments is unlikely to be due to changes in clay mineralogy. There are some noticeable clay mineralogy variations between the two sites but it is not the absolute between-site differences that are important here, rather that variations

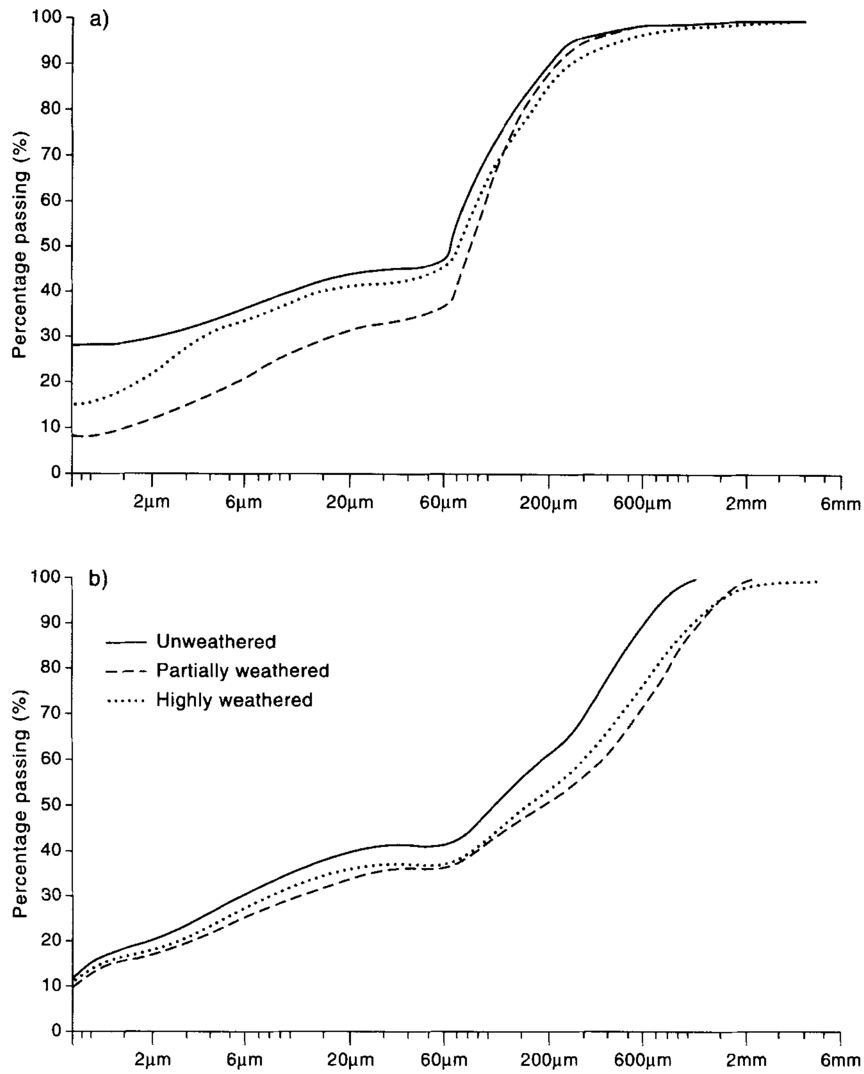

Figure 11. Cumulative particle size distribution curves: (a) Barbados; (b) Taiwan

within sites for different weathering states are small and that relative comparisons of behaviour at the different weathering grades are possible.

The particle size distribution characteristics are presented as cumulative frequency distribution curves (Figure 11). The results reinforce the conclusions of the mineralogy variations in that there is no marked overall reduction in particle size as the sediment weathers. It might be expected that rapid weathering is accompanied by a breakdown in the larger mineral grains and an associated change in clay mineralogy as particles disintegrate to increasingly stable forms. For both the Joe's River Formation and the Lichi Melange it seems highly likely that because material is removed from slopes by mass transport processes in a short time, mineralogical alteration does not have time to take effect. The liquid limit, plastic limit and plasticity index data (Table III) further confirm this, with no significant change to the data between unweathered and highly weathered samples for Taiwan or Barbados.

The most significant variations in physical properties are revealed by a consideration of the bulk density, moisture content and porosity (Table III). For both the Joe's River Formation and the Lichi Melange, porosity gradually increases as weathering effects become greater. The porosity increase is accompanied

Table III. Results of the physical property tests

Test material	Degree of weathering	Depth in profile (cm)	Plastic limit (%)	Liquid limit (%)	Plasticity index	Bulk density ($g cm^{-3}$)	Moisture content (%)	Porosity (%)
Joe's River	High	0–40	20·27	40·33	20·06	1·91	32·28	46·70
	Partial	40–80	19·36	29·29	09·93	2·04	29·60	38·00
	None	80–125	22·81	42·79	19·98	2·10	22·00	32·01
Lichi	High	0–40	20·14	31·00	10·86	2·19	12·91	25·4
	Partial	40–80	20·34	34·94	14·60	2·28	10·52	22·3
	None	80–125	19·31	31·48	12·17	2·36	09·26	20·1

by higher moisture contents as void spaces fill with water. Changes in porosity and moisture content alone suggest how the sediments are likely to behave both in a mechanical context and geomorphologically in the field on valley-side slopes. The bulk density results reflect the trend of the former two physical properties. As porosity and moisture content increase, so bulk density drops, indicating a swelling of the mineral matrix. The phase relationship changes as void space rises in proportion to the total mineral material.

Of greatest significance to the study are the changes to the geomechanical properties of the Joe's River Formation and the Lichi Melange, and the links with physical properties and landform development. It is important to remember that after isotropic consolidation, each sample was subjected to undrained shear and therefore an increasing axial deviatoric stress with no loss of pore fluid. It can thus be assumed that the mineral grains and pore fluid are incompressible and that the specimen volume is constant. The resulting deviatoric stress can be plotted against mean effective stress as a stress path and there is no need to consider volume.

The shape of the stress paths for unweathered, slightly weathered and highly weathered Joe's River Formation (Figure 12a) and Lichi Melange (Figure 12b) sediments give an indication of how the mechanical properties of the materials change during weathering. As expected, the stress paths for the unweathered and highly weathered material suggest that the former is geotechnically stronger and more competent than the latter. A plot of the critical state lines (Figure 13) drawn from the stress paths indicates the same. Surprisingly though, the strength of both materials rises from the unweathered to the partially weathered state, a conclusion indicated by stress paths (Figure 12) and the critical state lines (Figure 13) for each degree of

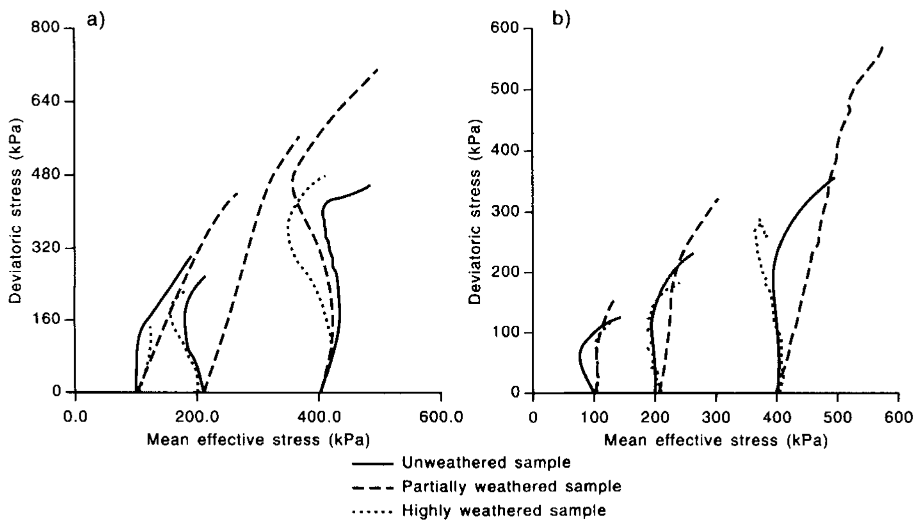

Figure 12. Stress path results: (a) Barbados; (b) Taiwan

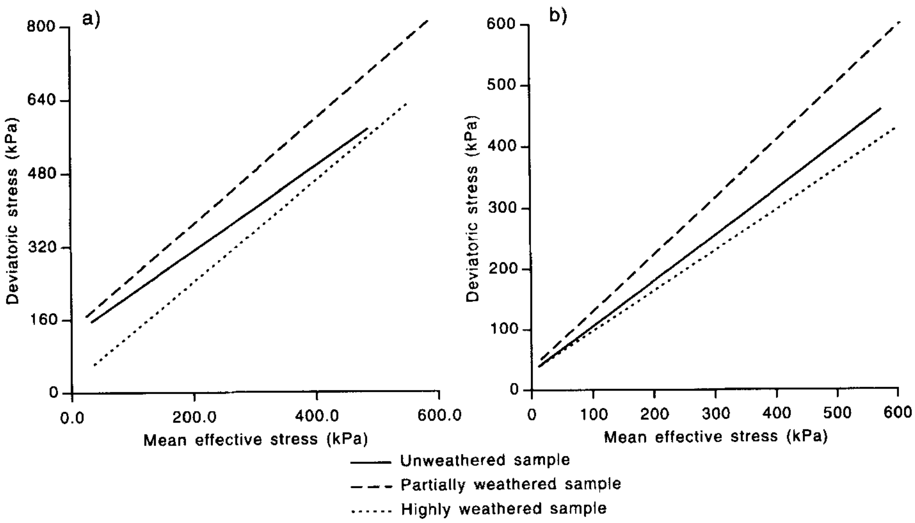

Figure 13. Critical state lines for the test materials: (a) Barbados; (b) Taiwan

weathering. The strengthening upon the onset of weathering followed by weakening occurs for both the Barbados and the Taiwan samples.

Plots of deviatoric stress against axial strain (Figure 14), a more conventional method of displaying stress–strain data in geomorphology, highlight the same trend. The plots represent tests completed for weathered, unweathered and partially weathered samples at confining pressures of 100, 200 and 400 kPa. For a given confining pressure, the partially weathered samples are the strongest. The Lichi Melange can be used as a specific example. At a confining pressure of 400 kPa, the shear strength results for unweathered, partially weathered and highly weathered samples are 340, 560 and 270 kPa, respectively.

There are many similarities and also some differences between data from the two sites. In both the Joe's River Formation and the Lichi Melange, pore space increases during weathering, a fact confirmed if specific volume and mean effective stress are plotted against each other (Figure 15). In the case of the Joe's River Formation, the unweathered sediment has a specific volume of around 1·48 and there is little change as the mean effective stress increases. For the highly weathered samples the situation is different, with the initial specific volume at the start of each triaxial cell test being between 1·8 and 1·9, and all samples showing reductions in the values as the mean effective stress is increased. At both sites there is also a strengthening effect which is induced as weathering commences and a softening effect as weathering continues. The most noticeable difference between Barbados and Taiwan samples is the variation in weathering-induced plasticity index changes, some difference in clay mineralogy and, despite similarity of behaviour, a generally lower strength for the Taiwan materials.

CONCLUSION

Important geomorphological implications arise from this study when comparing the quantitative laboratory data with a qualitative description of the landforms which develop on the scaly clay sediments. In both Barbados and Taiwan, outcrops of scaly clay are mantled with rapidly degrading slopes in which deeply incised gulley systems have developed. As weathering alters the materials there is rapid and frequent down-slope transfer of sediment, partly by surface wash and overland flow processes, partly by shallow landslide and other mass movement processes. The badlands which develop as a consequence of the mass wasting seldom generate a vegetation cover. At places, particularly in topographic lows, there may be a thick horizon of highly weathered material, while on steeper slope sections and topographic highs, the depth of the weathering horizon is small.

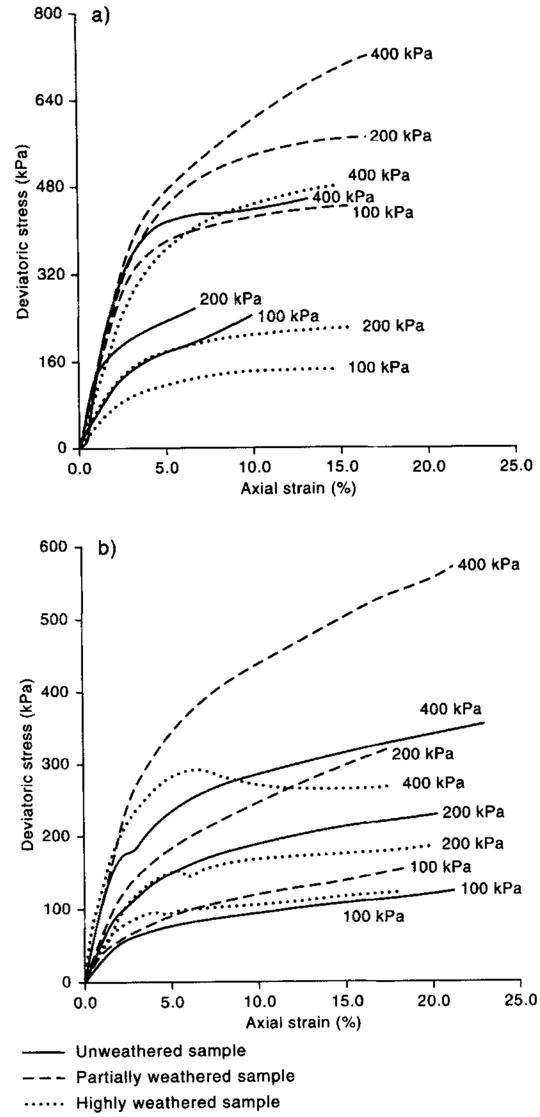

Figure 14. Stress–strain plots: (a) Barbados; (b) Taiwan

A tentative model can be suggested which links the geotechnical and geomorphological evidence. The best starting point is immediately after weathered debris has been removed from a slope, leaving fresh scaly clay exposed to tropical weathering processes. As weathering commences, pore volume will begin to increase slightly and strength goes up. The strength increase is associated with a gradual breakdown of the scaly clay structure which, it ought to be remembered, is one of highly polished, slickensided surfaces. The strength change at this point is a product of changes across fabric interfaces rather than of changes within individual fabric units. Further research is now in progress to examine this in greater detail. As weathering continues, the whole of the mineral matrix begins to expand and because of the typically tropical climate, the increase in void space is accompanied by an increase in moisture content as water permeates into the sediment. As the stress paths and critical state lines suggest, continued weathering results in a drop in the angle of internal friction of the material. Eventually the scaly clay becomes unstable and mass movement occurs. Because the interaction between weathering, changes in scaly clay properties and landslide

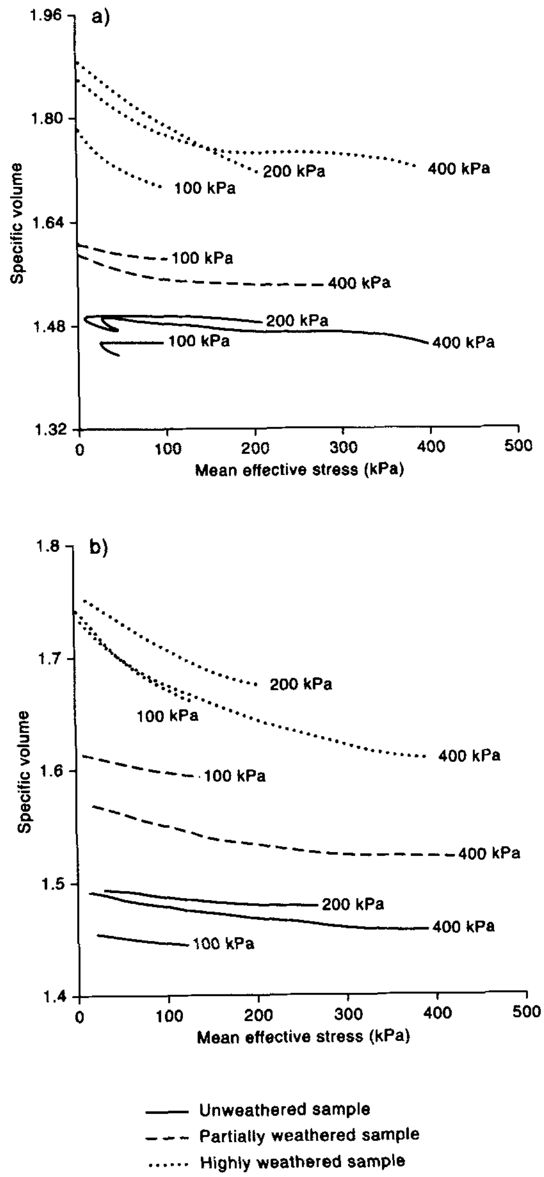

Figure 15. Relationship between specific volume and mean effective stress for the test materials

occurrence is ubiquitous across an outcrop, the result is the evolution of badlands. Of particular importance in the context of the Joe's River Formation and the Lichi Melange is the scaly fabric of the material, the rapid increase in pore volume upon weathering and the remarkably rapid change in geotechnical characteristics. The physical properties of scaly clay change rapidly under tropical weathering. Clay mineralogy shows no significant change, but geotechnical properties show marked weathering-induced differences.

In conclusion, it is important to recognize that it is not just an evaluation of the yield or shear strength characteristics of the materials which permits an explanation of geomorphological activity but a full appreciation of the geotechnical behaviour of the sediment under both isotropic compression and undrained shear. The critical state model permits a comprehensive consideration of the geotechnical

response of the sediments to weathering. Perhaps there are implications here for similar studies in soft sediments which set out to examine the interactions between geotechnics and landscape development.

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